NASA's CubeQuest Challenge – From Ground Tournaments to Lunar and Deep Space Derby

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The First Flight of NASA's Space Launch System will feature 13 CubeSats that will launch into cis-lunar space. Three of these CubeSats are winners of the CubeQuest Challenge, part of NASA's Space Technology Mission Directorate (STMD) Centennial Challenge Program. In order to qualify for launch on EM-1, the winning teams needed to win a series of Ground Tournaments, periodically held since 2015. The final Ground Tournament, GT-4, was held in May 2017, and resulted in the Top 3 selection for the EM-1 launch opportunity. The Challenge now proceeds to the in-space Derbies, where teams must build and test their spacecraft before launch on EM-1. Once in space, they will compete for a variety of Communications and Propulsion-based challenges. This is the first Centennial Challenge to compete in space and is a springboard for future in-space Challenges. In addition, the technologies gained from this challenge will also propel development of deep space CubeSats.

Nomenclature

ARC	=	Ames Research Center
BCT	=	Blue Canyon Technologies
CDR	=	Critical Design Review
ConOps	=	Concept of Operations
COTS	=	Commercial Off-The-Shelf
CU-E^3	=	University of Colorado Earth Escape Explorer
DSN	=	Deep Space Network
EDU	=	Engineering Development Unit
EM-1	=	Exploration Mission 1
GRC	=	Glenn Research Center
GT	=	Ground Tournament
I_{sp}	=	Specific Impulse
LEO	=	Low-Earth Orbit
MCR	=	Mission Concept Review
mN	=	milinewtons
MSFC	=	Marshall Space Flight Center
PDR	=	Preliminary Design Review
RACP	=	Resilient Affordable CubeSat Processor
SAR	=	System Acceptance Review
SDR	=	Software Defined Radio
SLS	=	Space Launch System
SRR	=	System Requirements Review

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STMD	=	Space Technology Mission Directorate
TID	=	Total Ionizing Dose
UHF	=	Ultra-High Frequency band
WFF	=	Wallops Flight Facility

I. Introduction – CubeSats and Government Challenges

A. CubeSats – Where are they now?

While CubeSats have been around for many years, they have stayed in the Low Earth Orbit (LEO) regime. Now that they have been established at the LEO level, and Commercial Off The Shelf (COTS) solutions have been successful on both the hardware and launch side of the mission, the next logical step is to take CubeSats beyond LEO. A successful Deep Space CubeSat mission will take more than just launching a LEO CubeSat into deep space, however. Two key technology areas that can be improved for deep space missions are communications and propulsion. For LEO CubeSats, propulsion is usually only necessary for attitude control functions (which can also be accomplished by other means). Radios also do not need to be terribly powerful and often run on amateur frequencies. Many companies and startups have been working on propulsion solutions and Deep Space Network (DSN) compliant radios, but have yet to actually fly them. With NASA's Space Launch System (SLS) launching 13 6U sized CubeSats into cis-lunar space in 2019, the time to prove out Deep Space CubeSats has come.

B. Government Challenges and NASA's Centennial Challenges

Government or corporate sponsored technical "challenges" have been around since the pre-industrial age. More recently, challenges have rewarded accomplishments in aerospace, including Charles Lindbergh's flight across the Atlantic in 1927, and Scaled Composite's Ansari X-Prize win in 2004. In 2005, NASA started the Centennial Challenge Program (CCP) as a way to incentivize development of relevant technologies in the private sector. Unlike large contracts with large overhead, the CCP focuses on technology and goals that student groups, startups and independent investors can participate in. Since its inception, the CCP has rewarded groups and individuals for developments in Astronaut Gloves, Regolith Excavation, and 3D Printed Habitats, among others.

II. A Brief History of the CubeQuest Challenge

With past Challenges being in the realm of rocketry and rovers, having a spacecraft design challenge centered on CubeSats seemed like a natural fit. With an industry ready for deep space launch opportunities, and with NASA's own deep space launch vehicle in development, the time for investment into deep space CubeSat technologies had come.

C. The Roots of CubeQuest

In 2013, a team was formed to investigate ways to incorporate the Centennial Challenge program with available space on EM-1. The team concluded that the CubeQuest Challenge should:

- Be exciting to the community
- Be objective and have clear and achievement-oriented goals
- Award those teams that are the "first" or "best"
- Be challenging enough to push the current technological boundaries, while also being achievable
- Stimulate the small sat industry
- Leads directly into NASA objectives
- Does not compete with current NASA missions

D. The Prizes

The CubeQuest Challenge is broken up into two parts – the Ground Tournaments are reviews, similar to the typical Design Reviews in the NASA parlance, where the teams are judged on the development of their designs. There is also the in-space portion of the Challenge, where team's satellites compete to achieve in-space objectives. This will be the first of NASA's Centennial Challenges to fly in space. Also of note, there is no requirement that the in-space teams must participate in the Ground Tournaments – if a satellite qualifies under the CubeQuest rules, it can be submitted in the Derbies.

1. Ground Tournaments

The Challenge consists of a total of four "Ground Tournaments." These are analogous to various design reviews. Each has their cash prize for the Top 5 teams, as well as qualifications for launch on EM-1. Teams that score in the Top 5 for Ground Tournaments 1 or 2, and score in the Top 3 for Ground Tournament 4 (as well as meeting certain scoring criteria and passing safety reviews) win a slot on EM-1. As of June of 2017, all of the Ground Tournaments have been completed, with the following prizes awarded:

Ground Tournament Winners			
Ground Tournament 1 August, 2015	MCR/SRR	CisLunar Explorers MIT KitCube Novel Engineering Ragnarok Industries Team Miles	$20,000 ea + EM-1 Eligibility
Ground Tournament 2 March, 2016	PDR	CisLunar Explorers CU-E3 MIT KitCube SEDS Triteia Team Miles	$30,000 ea + EM-1 Eligibility
Ground Tournament 3 October, 2016	CDR	Team Miles CisLunar Explorers CU-E3 MIT KitCube SEDS Triteia	$30,000 ea
Ground Tournament 4 June, 2017	CDR-SAR	CisLunar Explorers CU-E3 Team Miles	$20,000 ea + EM-1 Manifest

2. Lunar and Deep Space Derby

The in-space portion of the Challenge is the Lunar Derby and the Deep Space derby. The individual Derbies themselves have subsections awarding prizes for propulsion and communications achievements as well as overall system robustness.

Lunar Derby	
Lunar Orbit	$1.5 M divided between all who achieve one verifiable Lunar Orbit
Best Burst Data Rate	$225,000 ($25,000 for second) for the largest volume of error-free data in a 30 minute period
Largest Aggregate Data Volume	$675,000 ($75,000 for second) for the largest cumulative error-free data volume over 28 days
Spacecraft Longevity	$450,000 ($50,000 for second) for the spacecraft with the largest number of days between the first data packet and last data packet received.

Deep Space Derby	
Farthest Communication Distance from Earth	$225,000 ($25,000 for second) for receiving at least one verifiable, error-free, satellite-generated data block from the farthest distance >4M km from Earth.
Best Burst Data Rate	$225,000 ($25,000 for second) for the largest volume of error-free data in a 30 minute period
Largest Aggregate Data Volume	$675,000 ($75,000 for second) for the largest cumulative error-free data volume over 28 days
Spacecraft Longevity	$225,000 ($25,000 for second) for the spacecraft with the largest number of days between the first data packet and last data packet received.

E. Ground Tournament 1

Ground Tournament 1, held in the summer of 2015, was the first graded round of the Ground Tournaments. Along with $20,000 in prize money, teams were competing for a Top 5 slot, which would help them in qualifying for a potential EM-1 launch slot. In terms of mission timeline, GT-1 represented what a Mission Concept/Systems Requirements Review (MCR/SRR) would be in the NASA realm. GT-1 was also the opportunity for teams to make their first impressions, and for judges to see where the competition was going. Out of the 13 teams that participated in GT-1, the Top 5 teams were:

1. *Team Miles, Tampa, FL*
2. *MIT KitCube, Cambridge, MA*
3. *Cornell CisLunar Explorers, Ithaca, NY*
4. *Novel Engineering, Coca Beach, FL*
5. *Ragnarok Industries, Wilmington, DE*

F. Ground Tournament 2

Ground Tournament 2 was held in the spring of 2016, and graded teams both on their improvement from GT-1, as well as making sure the missions were at a Preliminary Design Review (PDR) level of maturity. At stake was $30,000 in prize money for each of the Top 5 finishers, as well as more eligibility for an EM-1 launch slot (for those teams not in the Top 5 for GT-1). The Top 5 of the 10 teams that participated in GT-2 were:

1. *Cornell CisLunar Explorers, Ithaca, NY*
2. *MIT KitCube, Cambridge MA*
3. *SEDS Triteia, La Jolla, CA*
4. *University of Colorado CU-E3, Boulder, CO*
5. *Team Miles, Tampa FL*

G. Ground Tournament 3

Nearly eight months separated GT-2 from GT-3, giving the teams ample time to improve their designs. GT-3 had no relevance when it came to EM-1 launch eligibility, but did offer a $30,000 price to the Top 5 finishers. GT-3 was analogous to a Critical Design Review (CDR) in NASA parlance, and teams had to show significant effort and confidence in their mission designs. This level of development brought the competition down to seven participating teams, the Top 5 being:

1. *Team Miles, Tampa, FL*
2. *Cornell CisLunar Explorers, Ithaca, NY*
3. *University of Colorado CU-E3, Boulder, CO*
4. *MIT KitCube, Cambridge, MA*
5. *SEDS Triteia, La Jolla, CA*

H. Ground Tournament 4

Ground Tournament 4 was the final on-earth tournament - the team’s final opportunity to show off their designs before launch. Teams that were in the Top 5 for either GT-1 or GT-2 must finish in the Top 3 for GT-4 to be eligible for an EM-1 launch opportunity. The Top 3 teams also received $20,000 in prize money. GT-4 was situated a year before delivery to SLS (for EM-1 teams), placing the tournament between a CDR and FRR in the traditional timeline. In terms of project schedule, many teams were in the middle of integration and testing activities, but nevertheless had data to show the judges, who had to project the likelihood of team’s progress until hardware delivery. The Top 5 teams were:

1. *Cornell CisLunar Explorers, Ithaca, NY*
2. *University of Colorado CU-E3, Boulder, CO*
3. *Team Miles, Tampa, FL*
4. *SEDS Triteia, La Jolla, CA*
5. *Ragnarok Industries, Wilmington, DE*

III. What Comes Next – The Teams and their Missions

Now that the Ground Tournaments are over, the remainder of the Challenge will happen in space. For 365 days after the launch of EM-1, the winning Ground Tournament teams (and any other teams that have acquired their own launch) will seek to fulfill their propulsion, communication, and longevity goals.

I. CisLunar Explorers

The CisLunar Explorers is a student-based team out of Cornell University that has been part of the Challenge from GT-1. Cislunar Explorers is competing in the Lunar Derby for Spacecraft Longevity. They are also the only team in the EM-1 group that are aiming for the Lunar Derby. Other mission goals for the Cislunar Explorers are to raise the TRL of electrolysis propulsion and optical navigation and to use as many COTS parts as feasible, along with open-sourcing their design so Small Sat developers can use their technology in the future.

One unique feature of Cislunar Explorer's satellite is after deployment, the 6U satellite will split off into two 3U-sized satellites. After this point, there are effectively two identical satellites with the same objectives and ConOps. Not only does this give mission redundancy, but it also allows for more experimental numbers when analyzing the spacecraft's performance.

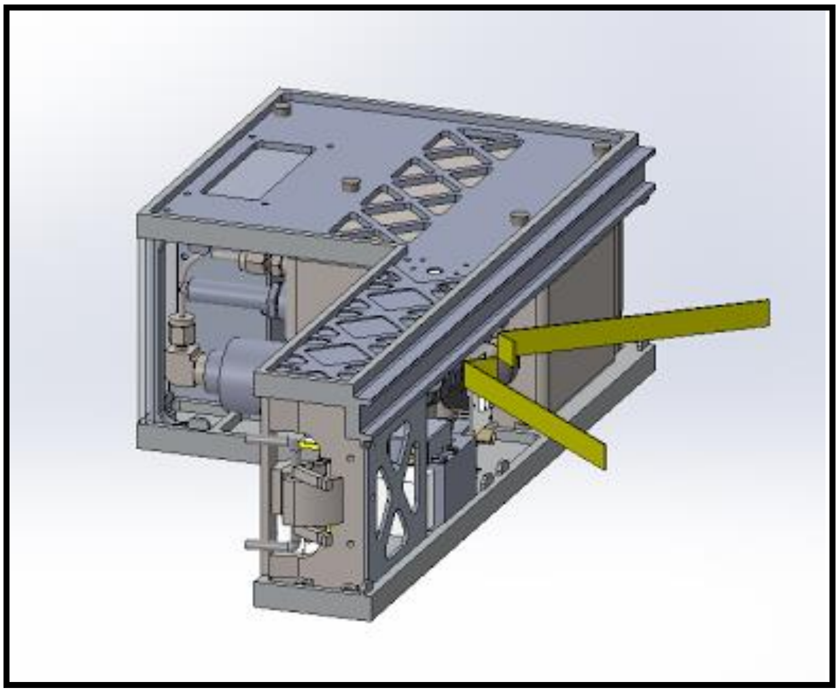

Figure 1. CAD Model of 3U section of CisLunar Explorer's satellite.

3. Lunar Orbit and Propulsion

Cislunar Explorers plan on using two Lunar Gravity Assists, along with a Lunar Orbit Insertion maneuver to achieve lunar orbit. Their estimated deltaV required for lunar orbit is 417 m/s, though their propulsion system is sized for 600 m/s. The primary propulsion on the satellite is an in-house designed water electrolysis system. The propulsion system consists of a large propellant tank (940 cm^3 capacity), electrolyzers, combustion chamber with spark plugs, and a custom designed, 3D-printed titanium nozzle. As of GT-4, the propulsion system has been tested extensively, including in a thermal vacuum chamber, and has fulfilled the mission requirements thus far.

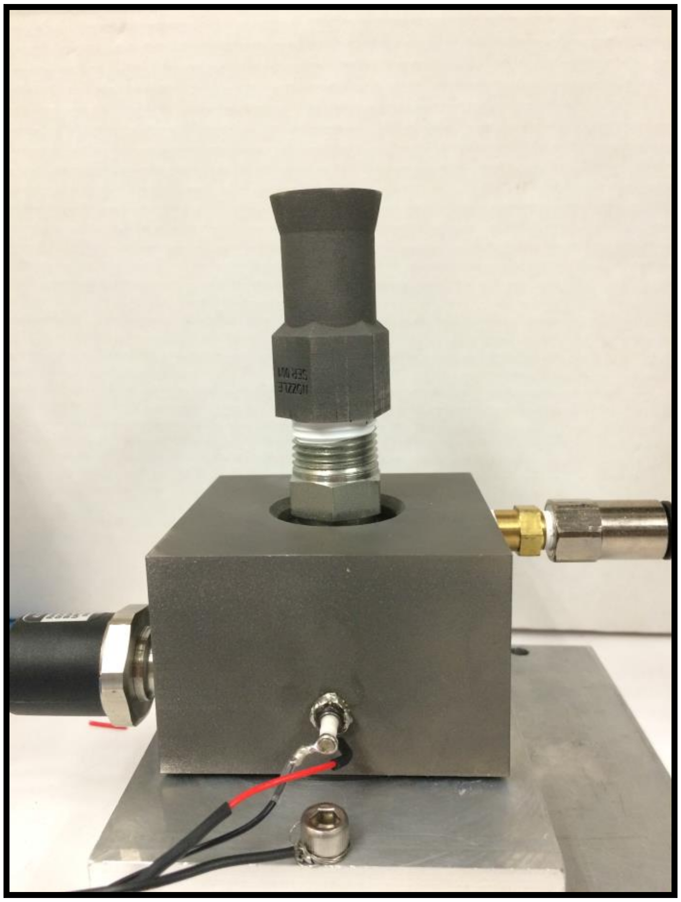

Figure 2. EDU of Propulsion System.

4. Attitude Determination and Control

The individual 3U-sized Cislunar Explorer satellites are spin-stabilized. In order to maintain the spacecraft roll, the team has characterized the slosh in their propellant tanks. The tanks themselves use the spin to separate out the electrolyzed ingredients (so the H_2 and O_2 do not get reintroduced into the water). The spin stabilization also means only one cold gas thruster is required for attitude control. This thruster is a simple CO_2 COTS canister and solenoid design.

Attitude determination is done with a series of Raspberry Pi camera modules, hooked up to the Raspberry Pi flight computer. Three cameras will catch glimpses of the Sun, Earth, and Moon, which can be used for trajectory determination.

5. Communications

Cislunar Explorers are doing all communications in the UHF spectrum, utilizing the existing ground station capabilities at Cornell University. In addition to the campus ground station, Cislunar has contracted with Wallops Flight Facility to use their 60ft UHF antenna for additional orbit tracking. The radio itself is based off of an AXSEM/ON Semi transceiver, with a custom breakout for use with the Raspberry Pi. The antenna is a half-wave dipole antenna, which is deployed off of the side of the spacecraft after spacecraft deployment. The antenna itself has a nearly omnidirectional beam pattern; when combined with the spin-stabilization, the satellite does not need precise pointing to link with the ground station.

Figure 3. Cornell University ground station antenna overlooking the campus

J. CU-E^3

The CU-E3 team is another student team, based out of the University of Colorado at Boulder. CU-E3 is participating in the Deep Space Derby, in all of the Deep Space Derby categories (Best Burst Data Rate, Largest Data Volume, Farthest Communications Distance, and Spacecraft Longevity). Cu-E3 is unique in that it does not carry any propulsion systems. The orbit plan allows the spacecraft to drift into a heliocentric orbit directly from the EM-1 deployment. The lack of propulsion also results in some clever ADCS control methods.

6. Attitude Determination and Control

CU-E^3's strategy for the Deep Space Derby is to drift from the EM-1 deployment site with no on-board propulsion. The attitude control options in Deep Space, without the use of propulsion, are limited. Cu-E3 uses an ADCS suite built by Blue Canyon Technologies, which is reaction-wheel based. In order to desaturate the reaction wheels, Cu-E3 plans to utilize the solar radiation pressure and the large surface area of their antenna to "push" their satellite, and keep the reaction wheels from ever becoming saturated. Coupled with the pointing requirements of the reflectarray antenna, this attitude control ConOps may be a novel mechanism for future small satellites out of Earth's magnetosphere.

7. Communications

CU-E3 is competing in all of the communications challenges in the Deep Space Derby. To achieve this, the team has designed a deployable reflectarray with a feed horn. This is an X-band antenna used for transmission of satellite data (used for challenge verification). The link design shows that Cu-E3 only needs the feed horn antenna to achieve their communications goals, but will be using the reflectarray antenna for extra margin, and for performance measurements. CU-E3 also carries S-band patch antennas, for receiving commands from the ground. CU-E3 has contracted with ATLAS for ground station services.

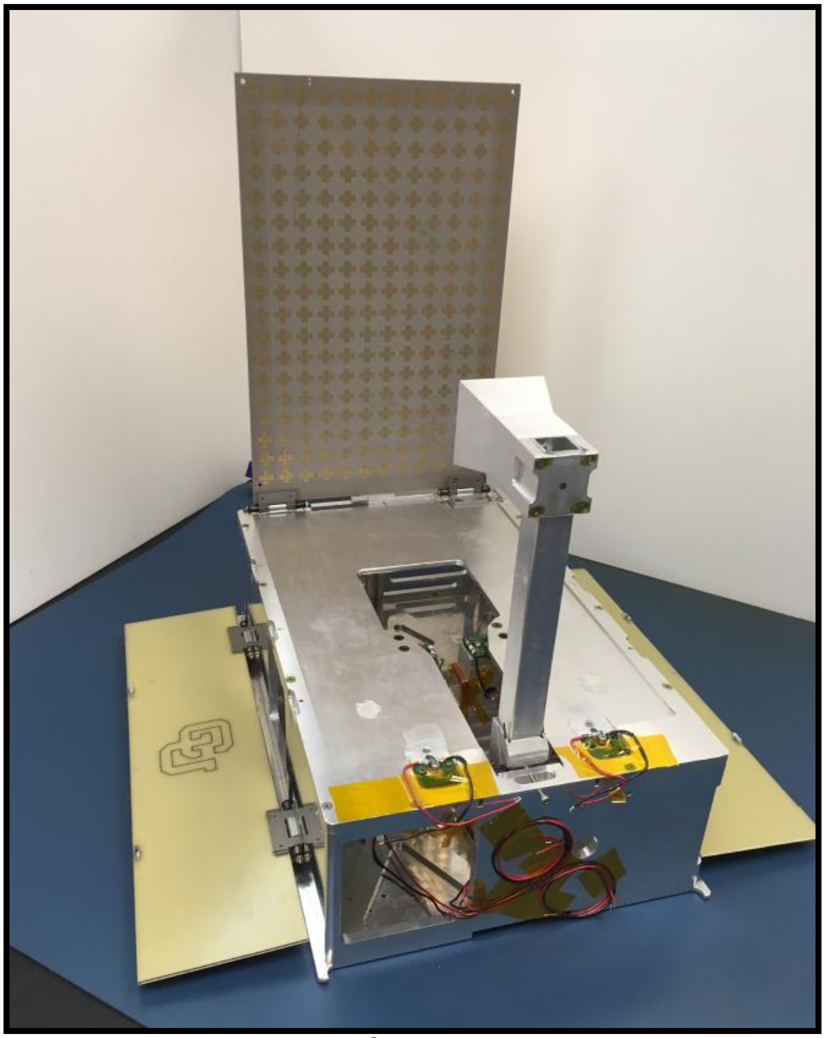

Figure 4. Structural EDU of CU-E^3, showing reflectarray and feed horn.

K. Team Miles

Team Miles is a team of “citizen scientists” who have novel ideas for CubeSat propulsion and radiation tolerance. The team is based out of a Tampa, FL “maker space,” and is an informal group of individuals interested in working on space projects. Team Miles is jointly related to Fluid and Reason LLC, a small business seeking to bring the ConstantQ thruster to market. CubeQuest is a platform Fluid and Reason is using to vet the ConstantQ design, raise its TRL, and build a base for future business.

8. Propulsion and Attitude Control

The ConstantQ thruster is central to Team Mile’s design. Not only is it the primary technology they aim to test, but it will be used in both primary propulsion and attitude control functions. The ConstantQ is an electrostatic thruster, using Iodine as propellent[1]. Each Model H unit (consisting of four thrusters) is capable of 5 mN of thrust and 760 sec of I_{sp}. The Team Miles satellite consists of 12 total thruster heads, which are canted, for use both as primary propulsion and for attitude control

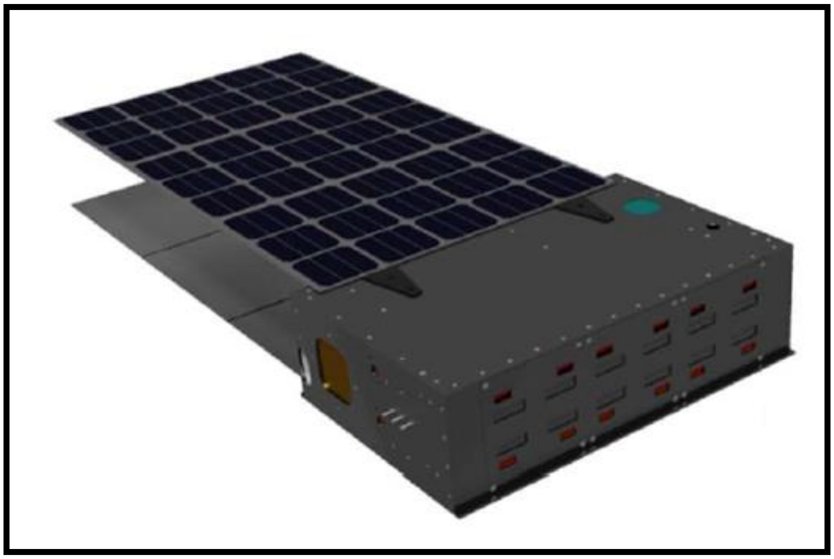

Figure 5. CAD model of Team Miles satellite, showing location of thrusters

Team Miles is competing in the Deep Space Derby – their propulsion will be used to push the satellite to the furthest distance possible from Earth (as well as attitude control). As such, the propulsion system is designed for the greatest volume feasible, as opposed to a specific ΔV (as would be the case for lunar orbit insertion). Nevertheless, Team Miles is planning for over 1,500 m/s of ΔV, which should take them 93 million km from Earth before the spacecraft shuts down.

9. Communications

NASA's DSN has offered free tracking services to all of the EM-1 qualified teams, in order to properly judge the team's orbits. Team Miles is the only EM-1 team to accept these terms. In addition, Team Miles has partnered with ATLAS to provide additional ground station services, including tracking and commanding. The Team Miles satellite is designed to be autonomous, and should only require tracking information and downlink of Challenge data, but can be commanded by ATLAS or DSN if necessary. To comply with the ATLAS and DSN standards, Team Miles communicates with a single S-Band SDR transceiver. Communications on the spacecraft run thru two patch antennas, located on opposite faces of the spacecraft, giving nearly omni-directional coverage. Team Miles is not aiming for any high data rate challenges, only the Farthest Distance from Earth communications challenge.

10. Radiation Tolerance

Another key to Team Mile's challenge strategy is radiation tolerance. Not only is radiation tolerance a key differentiator between LEO and Deep Space missions, it is also a currently underserved component of the CubeSat market. Team Miles has designed the RACP, a radiation tolerant flight computer, to serve as the backbone to their satellite. The RACP is an ARM processor mixed with a radiation tolerant microcontroller to provide fault tolerance along with a scalable design. The aim with the RACP is similar to the ConstantQ, in which both devices can gain flight heritage, in addition to data gathering for future commercial endeavors. In addition to the RACP, Team Miles has also TID tested all of their in-house electronics. The RACP, combined with TID-tested electronics and a ConOps designed around radiation tolerance sets the team up for Deep Space success.

L. Other Teams – 3rd Party Launch Opportunities

The In-Space Derbies are not just open to EM-1 teams, but to any team that meets the Challenge requirements. Teams will need to register and provide size and weight verifications as well as meet the safety and integration requirements of their launch providers.

IV. Conclusion

The CubeQuest Challenge was designed to stimulate development in Deep Space Small Satellite technologies. Thru the competition, three satellites with innovative propulsion, communications, and radiation-tolerant technologies are slated for launch on NASA's next deep space launch vehicle. The technologies developed for the competition will also be available to the public at large, either as commercial products or as open-source hardware. The $5m prize purse is an investment NASA is making in propelling CubeSat technology into Deep Space, and is far less than what would be spent on a singular NASA mission. The three selected EM-1 secondary payloads and any additional competitors will be competing in a unique race for space, and the small sat community will reap the rewards.

Acknowledgments

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[1]Faler, W.G., and Smith, D.R., Dunedin, FL, U.S. Patent Application for "Hybrid Electric Propulsion for Spacecraft," Docket No. 61/779,378, filed March 13, 2013.